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ACCELERATORS WITH A CLOSED HALL CURRENT

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Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
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З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

Part Two

Plasma Accelerators with Closed Electron Drift (Narrow Acceleration Zone)

ACCELERATORS WITH A CLOSED HALL CURRENT

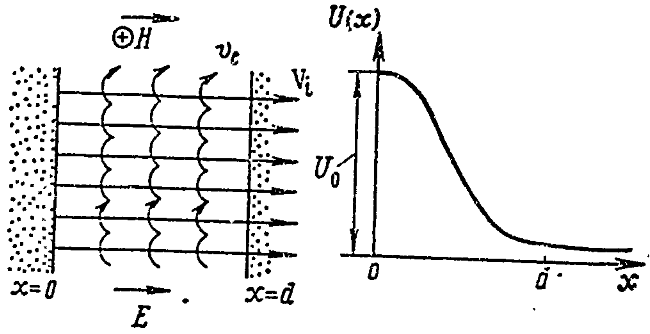
In the last decade studies have been made in the institutes of the Soviet Union and in a number of foreign firms on different types of plasma magnetohydrodynamic accelerators, including accelerators with a closed Hall current [7, 12, 13].

The working principle of the Hall accelerator is based on a sharp decrease in the transverse mobility of the electron component of the plasma in a strong magnetic field. For this reason it has been possible to create considerable strength of the electrical field perpendicular to the magnetic field with extremely low electron current densities in the same direction. Under these conditions the electrical field works primarily on ions, increasing their kinetic energy.

The pattern of motion of the ions and electrons in this accelerator is schematically shown in figure 1a; in figure 1b we see the distribution of the potential U(x) with respect to the thickness of the accelerating layer d.

In the plane x=0, which is parallel to the magnetic field H_z, we find some kind of ion source, for example, gas-discharge. It has a certain positive potential U_0 with respect to the plane x=d. If the thickness of this layer satisfies the inequality

$$\varrho_e(U_0) < d \ll \varrho_i(U_0), \qquad (1)$$



(a) (b)

Figure 1

where $\rho_e(U_0)$ and $\rho_i(U_0)$ are the Larmor radii of the electrons and ions at energy eU_0, then the electrons drift at a rate of $\frac{(\vec{E}\times\vec{H})}{H^2}$ along equipotential surfaces, while the ions are accelerated in the direction of the electrical field E_x virtually without experiencing the effect of magnetic forces.

The kinetic energy of the accelerated ions $\frac{MU_i^2}{2}$ is determined by the difference of potentials:

$$\frac{MU_i^2}{2}=e(U_0-U_d), \tag{2}$$

while useful work equals

$$A_i=j_{ix}(U_0-U_d), \tag{3}$$

where j_{ix} is the density of the ion current.

In the approximation of paired collisions the velocity of the electrons has two components which are normal to the magnetic field:

$$v_{ey}=-\frac{cE_x}{H_z}\frac{\omega_e^2\tau_e^2}{1+\omega_e^2\tau_e^2},$$
$$v_{ex}=-\frac{cE_x}{H_z}\frac{\omega_e\tau_e}{1+\omega_e^2\tau_e^2}. \tag{4}$$

Here $\omega_e\tau_e$ is the Hall parameter, or the magnetization parameter of the electrons.

When $\omega_e \tau_e >> 1$ the drift rate $v_{ey} \to -\frac{cE_x}{H_z}$, while the rate of movement in the direction of the electrical field

$$v_{ex} \to -\frac{cE_x}{H} \frac{1}{\omega_e \tau_e} \to 0.$$

For the accelerator to work effectively requires unhindered electron movement or a uniform accelerating layer in the drift direction ($\vec{E}\times\vec{H}$), and this is achieved in different systems with closed electron drift or a closed Hall current. In an accelerator with a closed Hall current the electrons are captured, as it were, within the accelerating layer. Their rate of drift from the layer v_{ex} is so insignificant that the corresponding decrease in the negative space charge is automatically compensated by the ionization of the residual gas or repeated ionization of the ions. Thus, for a stationary acceleration regime an artificial electron source is not required. It is sufficient to merely apply the difference in potentials U_0.

Since in the accelerating layer there occurs a quasi-neutrality, then the acceleration process cannot be formally described by magnetohydrodynamic equations of motion, i.e., as the acceleration of a single volume of plasma by ampere force and pressure gradient P. Consequently, we remove the limitations in the density of the ion current imposed by the space charge, and the limiting capabilities of the accelerator are determined by the following integral balance of forces applied to the accelerating layer:

$$\frac{j_{ix}}{e} MU_{ix} = \Delta\left(\frac{H_z^2}{8\pi} + P\right) = \int_0^d \frac{j_{EH} H_z}{c} dx, \qquad (5)$$

where j_{EH} is that part of the density of the Hall current caused by the electrical drift of ions at a rate of $v_{ey} = -c\frac{E_x}{H_z}$. Hence we

see that the density of the ion current can have a very high value, which is limited by the voltage of the external magnetic field $j_{ix} \sim \frac{eH_0^2}{8\pi M U_{ix}}$.

If we consider the ionization processes by the electrons of the residual gas and the possible drift of electrons toward the walls of the accelerating chamber along the magnetic field, the equation of continuity for the transverse electrical current j_{ex} can be written as follows:

$$\frac{dj_{ex}}{dx} = e\nu_{эфф} n_e, \qquad (6)$$

where n_e is the concentration of electrons; $\nu_{эфф}$ - effective rate of ionization.

The real rate of ionization ν_i exceeds quantity $\nu_{эфф}$ by a value proportional to the density of the longitudinal electron field which drifts towards the walls of the accelerating chamber. Specifically, if all electrons formed as a result of ionization drift along the magnetic field, then $\nu_{эфф}=0$.

From equality (6) it follows that the maximal electron current in the plane x=0 when $U=U_0$ equals in order of magnitude

$$j_{ex}(0) \approx e\nu_{эфф} n_e d. \qquad (7)$$

On the other hand, this current can be expressed as the transverse mobility of the electrons $b_\perp$:

$$j_{ex}(0) \approx e n_e b_\perp \frac{U_0}{d}. \qquad (8)$$

From equations (7) and (8) we can determine the thickness of the accelerating layer regardless of the density of the ion current:

$$d \approx \sqrt{\frac{\nu_0}{\nu_{эфф}}}\, \rho_e(U_0), \qquad (9)$$

where ν_0 is the diffusion scattering frequency of electrons.

If there is no longitudinal electron drift, then when $\nu_{эфф} = \nu_i$ the thickness of the layer will be minimal, on the order of the Larmor electron radius $\rho_e(U_0)$, and will not depend on residual gas pressure, since both ν_0 and ν_i are proportional to the concentration of neutrals. In the extreme opposite case all electrons formed in the volume drift along the magnetic field $\nu_{эфф} \to 0$, and an external source is required to maintain a finite value d.

From this discussion it is apparent that by regulating the longitudinal drift of electrons we can change the thickness of accelerating layer or the strength of the electrical field $E_x \sim \frac{U_0}{d}$.

Thus, in the general case an accelerator with a closed Hall current can have a certain forced distribution of the potential on the walls of the accelerating chamber $U_{CT}(x)$, while the plasma potential U(x) will follow the potential of the walls with an accuracy up to a quantity on the order of the temperature of the electrons T_e, as shown in figure 2.

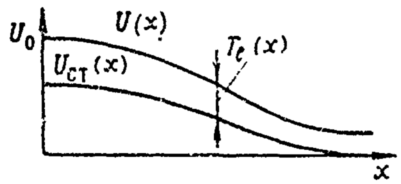


Figure 2

If the walls of the accelerating chamber are not sectioned, are made of metal, and are maintained at zero (cathode) potential, while the accelerating voltage U_0 applied to the ion source constitutes several kilovolts, then in practice we get the case with high effective ionization frequency $\nu_{эфф} \simeq \nu_i$, maximal voltage in the electrical field E_x, and an accelerating layer $d \approx \rho_e(U_o)$ of corresponding minimal thickness. For convenience let us call this accelerator modification the limiting Hall accelerator.

The second modification is relatively easy to achieve. This is the accelerator with a dielectric acceleration chamber[1]. The surface potential of the dielectric accelerating chamber corresponds to a zero resultant current toward the wall, i.e., to equality $j_{e\ \text{ст}}=j_{i\ \text{ст}}$ of the electron and ion components. Since $j_{i\ \text{ст}}\neq 0$, then $\nu_{\text{эфф}}<\nu_i$, and the accelerating layer is increased as compared to the limiting. This accelerator can be called the Hall nonlimiting accelerator.

Apparently there is no fundamental difference between limiting and nonlimiting accelerators with a closed Hall current, and both of these modification belong to the so called "E-systems."

The different theoretical aspects of the limiting Hall accelerator have been studied in [2, 3, 9, 10] in an approximation for a strong external magnetic field, where the natural field of the Hall current I_H could be ignored, i.e.,

$$\Delta H_z=\frac{4\pi I_H}{c}\ll H_0. \tag{10}$$

Note that under condition (10) the density of the ion current, as we see from equation (5), is proportional to the drift electron current I_{EH} and equals

$$j_{ix}=I_{EH}/\mathfrak{L}_i(U_0). \tag{11}$$

In the studies indicated above the structure and evolution of the accelerating layer have been closely followed as a function of the voltage of the magnetic field, anode voltage, and concentration of neutrals. One of the most important branches to be studied is that of the burn-up process (ionization) of the flow of neutrals from the ion source. With this plan it could be shown that an

[1]See Part Three of this book.

accelerator with a closed Hall current permits the use of ion sources with low ionization efficiency and can also work without an ion source in an independent discharge mode. Furthermore, in the general case the high efficiency condition of the limiting accelerator has the form of

$$j_{ex}(0)\overline{U_e(0)} \ll j_{ix}(d)\overline{U_{ix}(d)}, \qquad (12)$$

where to the left we have the power conveyed by the electron to the anode, to the right - the useful power of the fast ion flux.

If from the ion source there are virtually no neutrals and ionization in the layer is negligibly small $j_{ex}(0) \ll j_{ix}(d)$, then condition (12) is fulfilled even when the average energy of the electrons $\overline{U_e(0)} \approx \overline{U_{ix}(d)} \approx U_0$ is high. However, theoretical examination in the diffusion approximation shows that efficiency may be high even when the flux of neutrals from the source is significant or even in an independent discharge regime, where only neutrals enter the layer from the source. Even though here the ion and electron currents are compared $j_{ex}(0)=j_{ix}(d)$, nevertheless, the average energy of the ions $\overline{U_{ix}(d)} \to U_0$, while the average energy of the electrons $\overline{U_e(0)}$ in a rather intensive neutral flux becomes $\ll U_0$. The increase average energy of the ions can be explained by the concentration of the neutral burn-up zone near the anode.

The simplest variation of an accelerator with a closed Hall current is the ion magnetron, whose arrangement is shown in figure 3. Located on the axis of the device, parallel to the uniform magnetic field, is a cylindrical anode or ion source A. The space around the anode is bounded by the cylindrical ion collector (K) and by cathode disks. The accelerating layer develops close to the anode, around which the Hall current is closed. The ions found in the source or inside the layer are accelerated radially and gathered by the collector K if their Larmor radius $\rho_i(U_0)$ is greater than the radius of the collector R_K. Note that the collector can have positive potential U_0, in which case a Penning

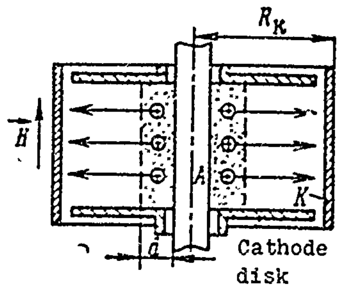


Figure 3. Ion magnetron.

discharge is obtained, and this can also be regarded as an accelerator with a closed Hall current.

In [4-6] studies were made on the structure of the accelerating layer in the geometry of the ion magnetron at a low gas pressure of $p<10^{-3}$ mm Hg without a special ion source. The physics of this high-vacuum discharge are extremely complex, and thus we list only certain experimental results.

- The thickness of the layer d in the studied range of discharge parameters ($H \leq 2.4$ kOe, $U_0 \leq 8$ kV) does not depend on gas pressure and is in satisfactory agreement with the theoretical estimates in the diffusion approximation.

- Generally discharge current I_p increases linearly with the voltage of the magnetic field, yet, contrary to the theory, only to a certain maximal value, at which we begin to observe a saturation or even a decline. Only by careful anodizing of the magnetic field was it possible to obtain a linear increase in the current over the entire working range, right up to H=2,400 Oe. The importance of this result in estimating the possibilities of an accelerator with a vacuum Hall current can be explained as follows.

According to equation (11) the maximal density of the ion current equals $j_{ix}=I_{EH}/\rho_i(U_0)$. On the other hand, for an independent high-vacuum discharge in a strong magnetic field, where the density of the ions in the layer can be ignored, the following relationships are valid:

$$\frac{H_0 I_{EH}}{c}=\frac{E_*^2}{8\pi},$$

$$j_{ex}(0)=j_{ix}(d)=j_p=e\nu_i n_e d=\frac{\nu_i}{4\pi}E_*, \quad (13)$$

where E_a is the strength of the electrical field on the anode. It is apparent that if discharge current I_p increases linearly with magnetic field H_0, then drift current I_{EH} is also proportional to H_0, and thus the limiting density of the ion current has a quadratic increase $\sim H_0^2$ [see equation (12)].

Thus, the given experiment ($I_p \sim H_0$) shows that with good anodizing to value the drift current increases linearly with the field H_0. Apparently, however, many experimental data do not permit relating the break-down in the linear dependence of $I_p(H_0)$ to merely poor anodizing [5, 16], but indicate that super-high-frequency (SHF) oscillations do play a substantial role.

In [5] regular peaks in the electron current on the cathode disks are revealed, which approximately follow the ionization frequency ν_i. The duration of these pulses is on the order of 10^{-7} s, but the average current is nevertheless comparable to the discharge current. The energy of the electrons with which they bombard the cathode disks constitutes several hundreds of volts, and thus they are usually anomalously called "fast."

The arrangement of the experiment in which the high-vacuum discharge with closed Hall current is used as the ion accelerator is shown in figure 4. A slit gas-discharge ion source is used as the anode. Here the accelerating layer is heterogeneous, since the electrons complete only an insignificant part of the closed drift path inside the ion beam. Since the Hall current under these conditions practically coincides with the vacuum-discharge Hall current, this is called an accelerator with a vacuum Hall current. The ultimate density of the ion current for this accelerator is limited:

$$j_i \approx I_{EH}/\varrho_i(U_0) \approx \frac{\nu_i}{\nu_0} \frac{\omega_e U_0}{4\pi \varrho_i(U_0)}. \qquad (14)$$

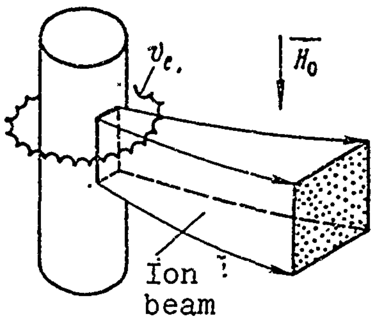


Figure 4. Ion accelerator with vacuum by-pass of Hall current.

In the experiments it was shown that accelerated strength $U_0 \gtrsim 10$ kV in the magnetic field $H_0 \gtrsim 10^{-3}$ Oe a well-formed beam can be obtained, of lead ions (M-207) for example, with a current density j_i of up to 100 mA/cm^2.

Thus, accelerators with a vacuum Hall current can compete successfully with electrostatic accelerators, since they possess such important advantages as the absence of ion optics.

In studying the acceleration of ions in a homogeneous layer with a closed Hall current a powerful gas-discharge source of thallium or lead ions served as the anode on the axis of the ion magnetron. A plasma column measuring (1.5-5) cm high and 1 cm in diameter, opened to 2π, served as the ion emitter. Since the accelerating layer in this arrangement was uniform in the drift direction, the Hall current was not limited. Thus, one could expect a substantial increase in the density of the ion current (satisfactory beam focus was maintained). The following results are of the greatest interest.

1. Current density in the ion beam under an accelerating force of $U_0 \gtrsim 1.5$ kV reaches saturation and is limited by the ionization rate of the vapors of the working metal in the source. In a special experiment with a forced source it was possible to obtain a beam with a current density of about 300 mA/cm^2 at an accelerating voltage of 2 kV and a magnetic field of ∿1,000 Oe. Since in this case beam geometry does not depend on current density, then the quasi-neutrality of the accelerating layer and the absence of limitations imposed on the density of the ion current by the face charge are confirmed.

2. At low accelerating voltages $U_0 \lesssim 1$ kV in the space between the ion source and the collector electrostatic "plugs," which block the beam, periodically develop. The "plugs" are cylindrical waves of excess positive charge, which are formed near the source and move slowly in a radial direction towards the collector. When gas pressure increases, when the emission of the electrons enters the ion beam along the magnetic field, or when there is an increase in accelerating voltage, the electrostatic "plugs" are surpressed. This phenomenon was given an interpretation analogous to Pierce electrostatic instability of the electron beam in a high vacuum, which results in the formation of a virtual cathode. The corresponding theory created for the one-dimensional case [1, 8] was qualitatively confirmed in many details by the experiment, and serves as a satisfactory guide in working with intense ion beams. However, certain aspects remain, as before, quantitatively and qualitatively unclear.

Results obtained from studying a powerful independent discharge in a stream of metal vapors (thallium, bismuth) conducted through a uniformly perforated anode tube of the ion magnetron[1] are of great practical significance. They confirm the high degree of ionization effectiveness in the layer in cases where the flux of neutrals had sufficient density and made it possible to create powerful ion sources based on a discharge with a closed Hall current.

Based on the experimental and theoretical results indicated above, the Hall accelerator was created which formed an intensive circular ion beam. The basic scheme of the accelerator is shown in figure 5. The circular source of the ions (И) lies in the gap of the electromagnet or the permanent magnet with radial magnetic field. Poles N and S simultaneously form the accelerating chamber. Positive potential U_0 is applied to the ion source. The electrons

[1]See "Two-stage acceleration of ions in a layer with a closed Hall current" on Russian p. 68 of this book.

achieve a closed azimuth drift; the ions are accelerated along axis z. The accelerator works in a high vacuum at a pressure of 10^{-4}-10^{-5} mm Hg.

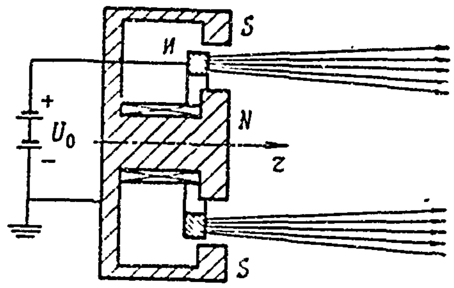


Figure 5. Circular ion accelerator with closed Hall current.

At a voltage of several kilovolts circular beams of bismuth ions with a current of up to 10 A are obtained. Power efficiency, which is determined as the ratio of the power captured by the ion catcher to total electrical power conducted to the accelerator, varies within a range of 0.7-0.9 in different regimes. When the accelerating voltage is reduced below a certain critical value the beam ceases to form, and almost all ions go to the magnetic pole. The phenomena which accompany this point to the electrostatic instability of the ion beam. However, for reliable interpretation currently existing data are not sufficient.

Thus, at the present time a rather large cycle of theoretical and experimental studies have been performed, which confirm the original physical premises of the accelerator with the closed Hall current and enable the creation of devices which form intensive stationary flows of accelerated plasma. The results which have been achieved justify recommendation of this type of accelerator as an effective new means of solving various physicotechnical problems.

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